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Leeward Deposition of Particles on Cylinders From Moving Aerosols

by
Gabrielle Asset
Thomas G. Hutchins

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FOREWORD

The work described in this document was authorized under Task 1C522301A06001, Basic Agents Investigation (U). This work was started in August 1962 and completed in June 1964. The experimental data are recorded in notebooks 7060, 7061, 7155, 7156, and 7157.

Acknowledgments

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Notices

Disclaimer

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Disposition

When this report has served its purpose, DESTROY it.

DIGEST

A study of leeward (back) deposition of moving aerosols on cylinders was conducted in a wind tunnel. Cylinder sizes were varied from 3.1 to 41 mm in diameter, aerosol particles from 4.0μ to 110μ in diameter, and wind velocities from 3 to 18 mph.

The ratio N_L:N_W, calculated from the experimental results, is defined as the ratio of the particle count of leeward and windward deposits on the cylinders. The impaction parameter, K, and the Reynolds number, R, of the flow around the cylinder were also calculated.

It is concluded that, in general, there is little leeward (back) deposition of particles over 100μ in diameter, an intermediate number of particles between 10μ and 100μ, depending on the conditions, and a large number of particles below 10μ in diameter at velocities from 3 to 18 mph.

When K was greater than the critical value of 0.0625, N_L:N_W was 0.4% or less, and, in general, showed no variation with particle size, cylinder diameter, and wind velocity.

When K was less than 0.0625, N_L:N_W ranged from about 0.5% to 131% and, in general, increased with cylinder diameter and with decreasing particle size and wind velocity.

Exceptions to this general behavior were found at R <300 and >10,000. In these regions, N_L:N_W was greater than expected. Since at these R's, vortexes are near, or at, the cylinder surface on the leeward side, it is probable that vortexes in the wake play a role in leeward deposition.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LEEWARD DEPOSITION OF PARTICLES ON CYLINDERS FROM MOVING AEROSOLS

I. INTRODUCTION.

Leeward deposition of particles from a moving aerosol has been reported by several workers. Yeomans et al.[1] reported that over twice as many particles were deposited on the back of a glass disk as on the front from an aerosol, mass mean diameter (MMD) 11.3μ, moving at 8 mph. Particles up to 28μ were deposited on the back.

Landahl and Herrmann,[2] using vertical slides in a wind tunnel, found that the deposit on the back of the slides from aerosols of MMD 4μ moving at 1 mph was equal to that on the front. Even when particles were 25μ, the deposit on the back was 37% to 66% of that on the front.

On the other hand, in connection with studies on deposition by inertial impaction on the upwind side of cylinders, Gregory[3] found that the downwind deposit was nil except for small deposits on the back of narrow cylinders at very low windspeeds.

Rosinski and Nagamoto,[4] in studying deposits of single layers of particles on cylinders covered with sticky substances, reported that the deposit of particles of 2μ was of the same order of magnitude on the leeward side as the windward side for velocities of 4.7 mph. At velocities of approximately 11 and 16 mph, the leeward deposition was greater than the windward by an order of magnitude.

In field studies* of deposition from windblown aerosols, it was reported that there was considerable deposition on the back of targets relative to that on the front. Since further information was needed on leeward deposition in connection with a number of problems in these Laboratories, it was decided to conduct a study of leeward deposition of particles under laboratory conditions.

II. EXPERIMENTATION.

A. Approach.

Glass rods coated with petrolatum were exposed in a wind tunnel to aerosols of polystyrene spheres. The rods were supported in a horizontal

* Gerber, B. Private communication. 1962.

position across the stream at a distance of 12 ft from the point where aerosols were introduced. After exposure of a rod, it was removed from the wind tunnel, put under a traveling microscope, and its surface scanned in order to count the number of particles deposited on back and front. From this count the ratio $N_L:N_W$ was computed, N_L being the number of polystyrene spheres counted on the leeward (back) side of the rod and N_W the number counted on the windward (front) side. Experimental conditions were varied by using glass rods 41, 21, 7.5, and 3.1 mm in diameter, aerosols composed of particles of four diameter ranges (4.0μ to 5.5μ, 10μ to 14μ, 19μ to 24μ, and 90μ to 110μ), and wind-tunnel airstream speeds of 18, 8.5, and 3 mph.

B. Materials.

1. Polystyrene Powder.

The powders that were dispersed in this work consisted of polystyrene spheres of specific gravity 1.06. The powders, classified according to particle diameter, fall into the following groups: 54μ to 154μ, 6μ to 77μ, 4μ to 27μ, and 1μ to 10μ.

2. Glass Rods.

The glass rods on which deposition was studied were 16 in. long and of various diameters (41, 21, 7.5, and 3.1 mm). Wooden plugs or collars were glued to each end of the rods to provide a means of supporting the rods and of attaching indicator pins. Indicator pins were actually heavy steel wire about 1-1/2 in. long, glued to the wooden plugs or collars, extending outward radially. The pins were used as reference points. When a rod was being exposed, the pin pointed in the leeward direction; when the rod was rotated, it was possible to measure the angle of rotation by measuring the rotation of the pin from its original position.

C. Equipment.

1. Wind Tunnel.

A schematic diagram (figure 1) shows the arrangement of the wind tunnel, the disperser, and accessory equipment.

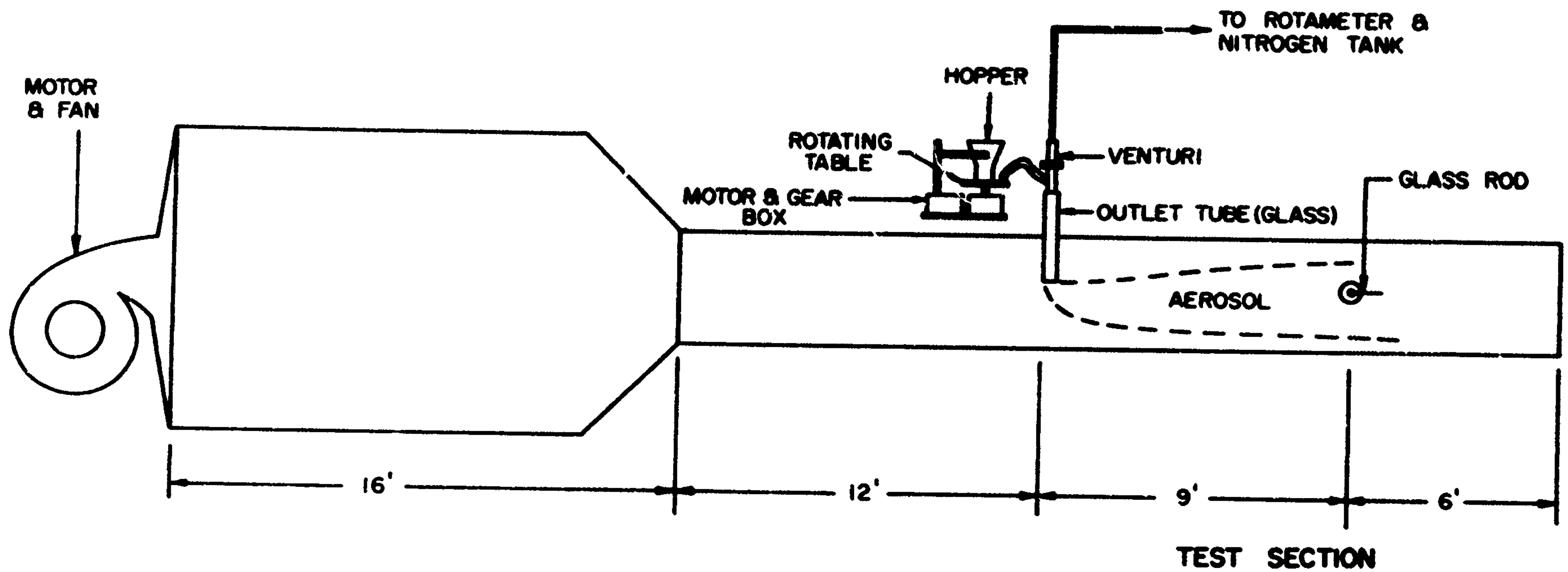

FIGURE 1

DIAGRAM OF EQUIPMENT

The tunnel, previously described,[5] produced an airstream of uniform velocity over an area 7 in. square in the center of the tunnel. The working section of the tunnel was 16 by 18 in. in cross section and 27 ft long. Airstream velocity was controlled by a motor generator set. In the work described in this report, the free-stream velocities were set at 18, 8.5, and 3 mph for each combination of particle size and rod diameter. No runs were made with the large spheres at 3 mph because they settled too rapidly to be carried to the glass rods.

2. Dispersers.

a. Hattersley-Maguire Disperser.

The smaller particles were introduced into the airstream through a glass tube, 2 cm in outside diameter (OD) and 1.8 cm in inside diameter (ID). The tube extended vertically from the outlet of a Hattersley-Maguire disperser[6] (placed on the top of the wind tunnel) into the airstream inside the tunnel. The disperser (figure 1) consisted of a hopper, a rotating table with a concentric groove 1/4 in. from its perimeter, a pair of scrapers, and a venturi nozzle. The inlet of the venturi nozzle was positioned just above the groove. The powder flowed from the hopper to the rotating table, where the pair of scrapers pushed the material into the groove. When nitrogen from a cylinder flowed through the venturi, the powder was sucked up in the venturi inlet and discharged into the 2-cm-OD outlet tube.

Different lengths and forms of outlet tubes were used for dispersing different powders. The tube used in dispersing the 6μ to 77μ and 4μ to 27μ powders extended to only the center of the tunnel, with the opening at the end of the tube facing downward. Although the powder was introduced at right angles to the flow, the particles were immediately entrained and traveled horizontally to the target. When the finest powder was introduced into the flow by this tube, the particles traveled upward, following the flow in the wake of the tube. To obviate the rise of the powder, a tube of the same diameter, but extending to the floor, was used. A 1-cm opening was blown in the side of the tube halfway down. The powder, upon leaving the orifice, traveled horizontally to the target.

b. Glass Funnel.

A glass funnel was used to introduce the largest spheres (90μ to 110μ) into the flow. These particles were not entrained in the main airstream when the Hattersley-Maguire disperser was used, but instead were deposited

beneath it on the floor of the tunnel. Thus, in lieu of the disperser, a glass funnel with a long, narrow stem was used to slow the speed of the spheres as they were ejected into the flow. The stem of the funnel was 26 in. long with 0.4-cm OD and 0.09-cm ID. The spheres were immediately entrained into the flow as they reached the funnel outlet.

In order to create the same size wake and disturbance in the flow as existed in the dispersion of the smaller spheres, the stem was surrounded by 2-cm glass tubing, which extended into the stream the same distance as in the case of the runs with smaller spheres.

3. Manometer.

The velocity of the airflow in the wind tunnel was measured by a thermopile anemometer, manufactured by Hastings-Radyst, Inc. Its precision was 7% of the scale reading after calibration against an inclined alcohol manometer. In the latter instrument, manufactured by Flow Corp., the vertical change in the liquid level was measured by a micrometer reading to 0.0001 in.

4. Traveling Microscope.

To study the deposit, the glass rods were mounted horizontally under a traveling microscope. The equipment was made from a bench lathe. Chucks on the headpiece and tailpiece were used to hold the rod for scanning. A protractor was made and mounted around the chuck of the tailpiece. As the rod was rotated during scanning, the steel pen and protractor made it possible to measure the angle of rotation from a reference direction.

Using a binocular microscope mounted on the movable crosspiece of the lathe and a Caywood Patterson graticule in one eyepiece, it was possible to count particles as small as 1.5μ with a magnification of 150.

D. Procedure.

1. Preparation of Powder.

The powders, consisting of particles of 54μ to 154μ and 6μ to 77μ were used without sieving. Powders consisting of particles of 4μ to 27μ and 1μ to 10μ, however, were sieved through a 325-mesh screen in order to reduce the size of the agglomerates. For each powder the proper dispersing outlet tube was used.

2. Exposure of Rods.

After a glass rod was thoroughly cleaned with soap and hot water, it was warmed in a drying oven and covered with liquid petrolatum. The petrolatum coating was allowed to cool and solidify. The rod was then clamped into position across the center of the tunnel, 12 ft from the disperser in a horizontal position across the flow. The wind-tunnel fan was turned on at the predetermined speed, and nitrogen gas was sent through the venturi for 3 min to stabilize the flow before the Hattersley-Maguire disperser was turned on. The rod was exposed for a suitable length of time, determined empirically. After exposure, the disperser was turned off, and the flows through the venturi and finally through the tunnel were stopped. The rod was removed from the tunnel and mounted under the traveling microscope.

3. Time of Exposure.

The exposure time of the rod to the aerosol was chosen by trial and error. The criteria for the proper time were that it should be sufficiently long to obtain a single-layered deposit, dense enough for a reliable counting, but sparse enough for ease in discriminating between single particles and agglomerates.

The exposure time varied considerably with particle size, stream velocity, and rod size. In runs with large particles, high velocities, and small rods, conditions were such as to obtain a high efficiency of deposition by the mechanism of inertial impaction; therefore, only 1 min was needed to cover the front with a single layer of polystyrene powder. On the other hand, in the runs with small particles, low velocities, and larger rods, as much as 30 min to 2 hr were needed to obtain enough particles to count. Under the latter conditions, the efficiency of inertial deposition was zero, and deposition occurred by some other mechanism.

In humid weather, with relative humidities of 50% and above, many agglomerates were formed in the powder consisting of 4μ to 27μ and 1μ to 10μ spheres. To obtain a sufficient number of single particles, exposure time was increased.

4. Scanning.

In scanning the rods, only the particles of a narrow size range in each powder were counted. The size range in each powder classification follows:

Powder classification Particle diameter, μ	Size range counted Particle diameter, μ
54-154	90-110
6-77	19-24
4-27	10-14
1-10	4.0-5.5

Counts were made only of particles lying in defined areas of the rod surface 0.1 or 0.05 in. apart along its length and at angular positions around the circumference, 10° apart. Only the lower half of the surface of the rod was scanned in order to eliminate the count of particles that were deposited by settling. The defined area, in most cases, lay within the boundary of the Caywood Patterson graticule; however, in the case of the 90μ to 110μ particles, this area included only two particles. In scanning the larger rods (41- and 21-mm diameters), therefore, the entire microscope field of view was used. In scanning the smaller rods (7.5- and 3.1-mm diameters), only a central strip of the microscope field was used, whose length was the diameter of the full field and whose width was the same as that of the graticule.

In all cases, at least 1,000 particles were counted on the windward side. In some cases, when the deposition was heavy, as many as 3,000 were counted.

5. Measurement of Wind Velocity.

Vertical- and horizontal-velocity surveys were made at a distance of 1 ft upwind from each rod at each velocity. The velocities were read from the meter on the Hastings anemometer and corrected according to the calibration chart. Separate surveys were made with the outlet tube used for dispersing the coarse powders and that used for dispersing the fine powders.

E. Computations.

1. Deposition.

The ratio $N_L:N_W$ was used as a measure of the leeward deposit. N_W was the total count on the windward side of the rod, and N_L was that on an equal area on the leeward side.

It might have been more meaningful, theoretically, to obtain an efficiency of deposition, E, which by definition is equal to the ratio D:A, D being the deposit per unit area per unit time on the surface of the rod and A the area dose of the moving aerosol. At the time of the commencement of this work, the effect of turbulence on sampling was not known. This method, therefore, was not feasible. In field studies, moreover, the back deposition had been related to windward deposition rather than to area dose. It was decided, therefore, to obtain the ratio $N_L:N_W$ instead of an efficiency ratio that involved the use of the area dose.

2. Inertial Parameter and Reynolds Number.

For each set of experimental conditions, the impaction parameter, K, was computed. K is defined as $\rho d^2V/18\mu D$, where ρ is the particle density, d the particle diameter, D the rod diameter, μ the viscosity of air, and V the velocity of the particle relative to the air near the object towards which the particle is moving. It has been shown by G. I. Taylor[7] that, for $K < 0.0625$ the particle moving near the cylinder never touches it, and deposition by the impaction mechanism does not take place.

Since it was expected that vortexes formed in the wake near the cylinder might affect leeward deposition, the Reynolds number, R, of the flow relative to the cylinder was computed. R is equal to DV/J, where J is the kinematic viscosity of the air.

III. RESULTS.

Table 1 shows the counts obtained on the leeward and windward sides of the rods, N_L and N_W, and the ratio $N_L:N_W$ expressed in percent for each run.

As shown in table 1A, there was only a very small deposition of particles of diameters between 90μ and 110μ at any windspeed on any rod.

As shown in table 1B, there was also a very small deposition of particles of diameters between 19μ and 24μ at 18 mph on any rod. At 8.5 mph, however, there was a greater deposition but only on the 41-mm rod, where $N_L:N_W$ was 0.69%. At 3 mph, there was an even greater deposition on three rods: $N_L:N_W$ was 2.5%, 0.49%, 0.05%, and 0.67% for rods of 41, 21, 7.5, and 3.1 mm, respectively.

TABLE 1

LEEWARD DEPOSITION OF PARTICLES FROM AEROSOLS

(Ratio of leeward count and windward count, $N_L:N_W$)

Run number	Stream velocity	Rod diameter	Time	Particle count N_L	Particle count N_W	$N_L:N_W$	Average $N_L:N_W$
	mph	mm	min			%	
A. Particle diameter, 90μ to 110μ							
470	18	41	2	5	1,476	0.34	
472			2	3	1,259	0.24	
491			2	6	1,264	0.47	
498			2	4	1,279	0.31	
500			2	6	1,298	0.46	0.34 ±0.08
469		21	1	0	1,151	0	
471			2	0	1,282	0	
492			2	1	1,205	0.08	
496			2	0	1,276	0	0.02 ±0.04
2		7.5	1	0	637	0	
5			1	0	747	0	
6			1	0	1,063	0	
493			1.5	0	1,409	0	0
494		3.1	1	0	1,292	0	
495			1	0	1,332	0	
497			1	0	1,257	0	
499			1	0	1,187	0	0
474	8.5	41	7	2	502	0.40	
476			3	0	1,178	0	
478			4	1	894	0.11	
481			6	0	737	0	
482			10	3	669	0.45	
501			5	0	476	0	0.16 ±0.17
473		21	4	0	502	0	
475			2	0	707	0	
477			3	1	1,313	0.08	
480			4	0	586	0	0.02 ±0.04
7		7.5	1	0	575	0	
21			1	0	476	0	
483			1	0	374	0	
484			2	0	334	0	0
485		3.1	1	0	321	0	
486			1.5	0	347	0	
488			1.5	0	293	0	
489			2	0	212	0	
490			3	0	233	0	0
B. Particle diameter, 19μ to 24μ							
538	18	41	20	2	1,262	0.16	
540			20	2	1,379	0.15	
542			20	3	1,225	0.24	
544			15	5	1,232	0.46	0.24 ±0.14
537		21	10	0	1,283	0	
539			15	0	1,269	0	
541			15	1	1,283	0.08	
543			15	0	1,269	0	0.02 ±0.04
2		7.5	–	0	1,333	0	
3A			–	1	2,143	0.05	
10A			–	0	2,080	0	
25			–	0	1,208	0	
30			–	0	2,023	0	
36			–	0	1,547	0	0.01 ±0.02
6A		3.1	–	0	1,789	0	
7A			–	0	2,034	0	
11			–	1	2,016	0.05	
38			–	0	1,804	0	
52			–	0	2,080	0	
62			–	1	3,100	0.03	
82			–	0	1,702	0	0.01 ±0.02

TABLE 1 (contd)

[illegible]	Stream velocity	Rod diameter	Time	Particle count N_L	Particle count N_W	$N_L:N_W$	Average $N_L:N_W$
	mph	mm	min			%	
530	8.5	41	30	8	1,184	0.68	
532			30	9	1,159	0.78	
534			20	8	1,241	0.64	
536			20	8	1,204	0.66	0.69 ±0.05
529		21	15	0	1,263	0	
531			15	0	1,192	0	
533			15	0	1,290	0	
535			20	0	1,350	0	0
1A		7.5	–	0	3,521	0	
4A			–	0	1,635	0	
9A			–	0	1,816	0	
11A			–	0	1,749	0	
27			–	0	3,126	0	
32			–	0	1,096	0	0
5A	8.5	3.1	–	0	1,840	0	
12			–	0	1,534	0	
48			–	0	1,690	0	
49			–	0	1,764	0	
56			–	0	1,188	0	
58			–	0	1,374	0	0
509	3	41	30	23	1,140	2.01	
513			30	27	1,096	2.46	
517			30	21	1,216	1.73	
520			30	42	1,307	3.21	
524			30	45	1,227	3.67	
528			30	23	1,222	1.88	2.5 ±0.7
508		21	30	5	1,235	0.41	
512			30	4	1,095	0.37	
521			30	5	1,107	0.45	
523			30	9	1,225	0.73	0.49 ±0.14
507		7.5	20	1	1,123	0.09	
511			20	0	1,179	0	
515			20	0	1,217	0	
519			20	2	1,255	0.16	
527			20	0	1,210	0	0.05 ±0.06
510		3.1	11	9	1,186	0.76	
514			10	7	1,435	0.49	
518			10	6	1,224	0.49	
522			10	13	1,413	0.92	
526			10	9	1,281	0.70	0.67 ±0.16
			C. Particle diameter, 10μ to 14μ				
232	18	41	80	31	1,284	2.42	
451			30	19	1,027	1.85	
454			30	41	1,200	3.42	
455			15	13	1,102	1.18	
457			15	17	1,243	1.37	2.1 ±0.7
336		21	15	2	1,256	0.16	
337			30	5	1,222	0.41	
338			30	5	1,239	0.40	
376			20	6	1,179	0.51	
450			20	2	1,023	0.20	
452			20	1	1,046	0.10	
456			20	3	1,108	0.27	0.30 ±0.1
72		7.5	15	1	3,040	0.03	
331			15	0	1,286	0	
332			15	0	1,232	0	
333			30	0	1,314	0	
334			30	2	1,226	0.16	0.04 ±0.06
52		3.1	30	0	2,080	0	
62			30	1	3,188	0.03	
74			30	2	2,564	0.08	
86			30	1	1,676	0.06	
90			30	2	2,520	0.08	
327			15	0	1,269	0	
328			30	1	1,272	0	
329			30	0	1,266	0	
330			30	1	1,309	0.08	0.05 ±0.03

TABLE I (contd)

Run number	Stream velocity	Rod diameter	Time	Particle count N_L	Particle count N_W	$N_L:N_W$	Average $N_L:N_W$
	mph	mm	min			%	
345	8.5	41	10	31	1,248	2.48	
349			15	40	1,235	3.24	
416			20	45	1,004	4.48	
423			15	71	1,215	5.84	
427			25	63	1,227	5.13	
466			18	28	1,039	2.69	4.0 ±1.6
372	8.5	21	25	30	1,062	2.82	
424			30	14	1,216	1.14	
426			40	33	1,214	2.72	
462			5	39	1,330	2.93	
463			5	26	1,048	2.48	2.4 ±0.7
126		7.5	15	0	1,454	0	
172			15	0	1,377	0	
187			15	0	1,211	0	
343			15	0	1,411	0	
347			15	2	2,412	0.08	
374			25	1	1,436	0.07	
421			20	0	1,209	0	
425			15	0	1,332	0	
428			20	0	1,227	0	0.02 ±0.03
134		3.1	10	0	2,556	0	
166			10	1	2,212	0.05	
170			10	0	2,062	0	
178			10	0	2,098	0	
182			10	0	2,706	0	
391			8	0	1,812	0	
413			8	0	1,235	0	
420			8	0	1,177	0	0
222	3.0	41	120	100	1,478	6.77	
234			120	65	1,018	6.39	
262			105	134	1,751	7.65	
263			120	107	1,379	7.75	
435			30	101	1,181	8.55	
436			90	95	1,212	7.84	
458			40	75	1,010	7.43	7.5 ±0.7
260		21	35	115	1,543	7.45	
438			75	89	1,003	8.87	
443			40	72	1,005	7.16	
459			20	73	1,014	7.20	
460			20	69	1,064	6.47	
461			20	101	1,086	9.30	7.7 ±1.0
192	3.0	7.5	20	40	1,325	2.99	
238			30	42	1,106	3.80	
240			13	70	1,819	3.85	
442			25	40	1,090	3.67	
444			11	41	1,021	4.02	3.7 ±0.4
196		3.1	30	26	1,040	2.50	
198			30	36	1,376	2.62	
200			30	16	1,449	1.10	
202			30	32	1,090	2.94	
210			10	33	2,091	1.58	
239			8	24	1,066	2.25	
241			6	45	2,813	1.60	
247			4	29	[illegible],195	2.51	
249			4	21	1,015	2.07	
433			30	20	1,120	1.64	
441			10	13	1,251	1.04	
464			20	28	1,011	2.76	
465			20	11	1,018	1.08	2 ±0.7
			D. Particle diameter, 4.0μ to 5.5μ				
548	16.6	41	40	1,023	1,205	84.9	
532			29	993	1,145	86.7	
556			30	1,021	1,195	85.4	
571			30	1,098	1,095	100	
577			60	1,098	1,072	102	92 ±8
549		21	30	1,364	1,207	113	
553			25	2,055	1,223	168	
557			20	1,488	1,260	118	
572			60	1,947	1,462	133	
578			60	1,300	1,057	123	131 ±19

TABLE 1 (contd)

Run number	Stream velocity	Rod diameter	Time	Particle count		$N_L:N_W$	Average $N_L:N_W$
				N_L	N_W		
	mph	mm	min			%	
550		7.5	16	25	1,210	2.06	
554			15	41	1,190	3.44	
558			15	15	1,390	1.08	
579			60	49	1,001	4.90	
595			12	27	1,139	2.37	2.8 ±1.3
551		3.1	10	7	1,254	0.56	
555			10	0	1,302	0.00	
559			10	1	2,128	0.05	
593			16	1	1,359	0.07	0.17 ±0.22
560	8.1	41	40	193	1,215	15.9	
564			30	103	1,052	9.8	
598			45	138	1,027	13.4	
603			40	154	1,074	14.3	13.4 ±2.2
561		21	29	210	1,623	12.9	
594			30	79	1,093	7.23	
597			30	76	1,336	5.69	
604			50	65	1,084	5.99	8 ±2.9
562		7.5	25	54	1,639	3.29	
583			60	32	1,078	2.97	
590			30	48	1,060	4.53	
599			15	83	1,083	7.66	4.6 ±1.8
563		3.1	30	44	3,127	1.41	
573			60	27	1,154	2.34	
589			115	19	1,225	1.55	
592			12	21	1,509	1.39	1.7 ±0.4
570	3.1 ±0.3	41	105	128	1,038	12.3	
596			60	115	1,045	11.0	
600			60	163	1,018	16.1	
605			60	86	1,079	8.0	12 ±3
567		21	40	103	1,103	9.3	
575			60	112	1,069	10.5	
580			60	164	1,087	16.3	
601			60	114	1,101	10.4	
613			95	115	1,061	10.8	11 ±3
574		7.5	60	400	1,269	31.5	
586			60	162	1,004	16.1	
607			60	292	1,050	27.8	
610			30	300	1,090	27.5	26 ±6
565	3.6 ±0.2	3.1	20	237	1,089	21.8	
568			30	221	1,046	21.1	
576			30	723	1,052	68.7	
582			45	813	1,091	74.5	
608			45	634	1,002	63.3	
611			45	197	1,021	19.3	
615			45	397	1,225	32.4	43 ±23

As shown in table 1C, there was, in general, greater deposition of particles with diameters between 10μ and 14μ. At 18 mph, there was significant deposition only on the largest rod of 41 mm where $N_L:N_W$ was 2.1%. At 8.5 mph, there was deposition on the two larger rods: $N_L:N_W$ was 3.4% for the 41-mm rod and 2.4% for the 21-mm rod. At 3 mph, however, there was significant leeward deposition on all rods: $N_L:N_W$ was 7.5%, 7.7%, 3.7%, and 2.0% for rods of 41, 21, 7.5, and 3.1 mm, respectively.

As shown in table 1D, $N_L:N_W$ was largest for particle diameters between 4.0μ and 5.5μ for a given wind velocity and rod diameter. At 16.6 mph, $N_L:N_W$ was 92% for the 41-mm rod and 131% for the 21-mm rod, at 7.3 mph it was 13.4% and 8%, and at 3.1 mph it was 12% and 11%, respectively.

Table 1 shows that the ratio $N_L:N_W$ was independent of duration of exposure. For example, $N_L:N_W$ for particles of 90μ to 110μ, deposited at 8.5 mph on the 41-mm rod, was 0%, 0.11%, 0%, 0%, 0.40%, and 0.45% for exposure times of 3, 4, 5, 6, 7, and 10 min, respectively. In another example (i.e., for particles of 10μ to 14μ, deposited at 18 mph on the 41-mm rod), $N_L:N_W$ was 1.4%, 3.4%, and 2.4% for exposure times of 15, 30, and 60 min, respectively.

Table 2 shows the average values of $N_L:N_W$, K, and R for each experimental condition; $N_L:N_W$ is expressed as percent. When K was greater than the critical value of 0.0625, $N_L:N_W$ was small, varying from 0% to less than 0.4%. On the other hand, when $K < 0.0625$, $N_L:N_W$ was larger, varying from about 0.5% to 131%.

Table 2 also shows the general trend. When K was greater than the critical value, $N_L:N_W$ was very small, or zero, and did not seem to be affected by particle size, cylinder diameter, or wind velocity. On the other hand, when K was less than the critical value, in general, $N_L:N_W$ decreased with cylinder diameter but increased with decreasing wind velocities and decreasing particle size.

Exceptions to these generalities can be found in table 2. The first was the deposition of 19μ to 24μ particles at 3 mph on the 3.1-mm cylinder where $N_L:N_W$ was larger than expected for $K > 0.0625$, and was, in fact, larger than those on the two larger cylinders. The second was the deposition of 4.0μ to 5.5μ particles at 16.8 mph on the 21-mm cylinder, where $N_L:N_W$ was 131%, whereas on the 41-mm cylinder it was only 92%. The third was the deposition of 4.0μ to 5.5μ particles at 3 mph on the 7.5- and 3.1-mm rods,

where $N_L:N_W$ increased with decreasing cylinder diameter. The Reynolds number in the first case was 277; in the second, 10,500 and 20,500; and in the third, 293. These anomalous results are explained in section IV, E.

Some of the results are graphed in figures 2, 3, and 4. Figures 2 and 3 show the graph of $N_L:N_W$ plotted against cylinder diameter for various particle sizes at wind velocities of 8.5 and 3.1 mph. In figure 4, $N_L:N_W$ is plotted against wind velocity for various particle sizes. These graphs show the general trends and the exceptions occurring at R = 277 and 22,000.

IV. DISCUSSION.

A. Variances in Results.

Wide variances existed in $N_L:N_W$. Such variances were to be expected when deposition was small on the leeward side of the rods, since small differences in a total of one to five particles of the leeward deposit would make a large difference in $N_L:N_W$.

Another cause of variance was in the relative number of agglomerations in the powders, which varied with the humidity. When there were many agglomerates, less leeward deposition occurred, even with a heavy windward deposition.

B. Discussion of Windward Deposit.

As shown in table 2, results can be divided into two groups: results occurring when $K > 0.0625$ and results occurring when $K < 0.0625$. When $K > 0.0625$ the small value of $N_L:N_W$ and the short exposure time needed to obtain an adequate deposit suggest that inertial impaction was the main mechanism of deposition on the windward side, and that the rate of deposition was rapid.

When $K < 0.0625$, the longer time required for deposition suggests another mechanism of deposition, which has been shown by Pereles[8] to be turbulent diffusion. The longer time of exposure required to obtain a satisfactory deposit shows that this process is slower than inertial impaction. That turbulence was present in the tunnel was shown by measurements made by a constant-current, hot-wire anemometer. The turbulent intensity, with the dispersal outlet tube extending halfway down into the tunnel flow, was found to be 4% to 5%.

TABLE 2

SUMMARY OF RESULTS

Particle diameter	Stream velocity	Rod diameter	$N_L:N_W$	Impaction parameter	Reynolds number
μ	mph	mm	%		
90-110	18	41	0.36	6.4	22,000
		21	0.02	12	11,300
		7.5	0	35	4,020
		3.1	0	84	1,660
	8.5	41	0.16	3.0	10,400
		21	0.02	5.9	5,320
		7.5	0	17	1,900
		3.1	0	40	785
19-24	18	41	0.24	0.26	22,000
		21	0.02	0.50	11,300
		7.5	0.01	1.4	4,020
		3.1	0.01	3.4	1,660
	8.5	41	0.69	0.12	10,390
		21	0	0.24	5,320
		7.5	0	0.66	1,900
		3.1	0	1.6	785
	3	41	2.5	0.04	3,660
		21	0.49	0.08	1,880
		7.5	0.05	0.23	670
		3.1	0.67	0.57	277
10-14	18	41	2.1	0.06	22,000
		21	0.30	0.13	11,300
		7.5	0.04	0.35	4,020
		3.1	0.05	0.85	1,660
	8.5	41	4.0	0.03	10,390
		21	2.4	0.06	5,320
		7.5	0.02	0.17	1,830
		3.1	0	0.40	785
	3	41	7.5	0.01	3,660
		21	7.7	0.02	1,880
		7.5	3.7	0.06	670
		3.1	2.0	0.14	277
4.0-5.5	16.8	41	92	0.015	20,400
		21	131	0.029	10,500
		7.5	2.8	0.082	3,750
		3.1	0.17	0.200	1,550
	8.1	41	13.4	0.007	9,920
		21	8.0	0.014	5,080
		7.5	4.6	0.039	1,820
		3.1	1.7	0.096	750
	3.1	41	12.0	0.003	3,880
		21	11.0	0.005	1,950
		7.5	26.0	0.016	720
		3.1	43.0	0.038	293

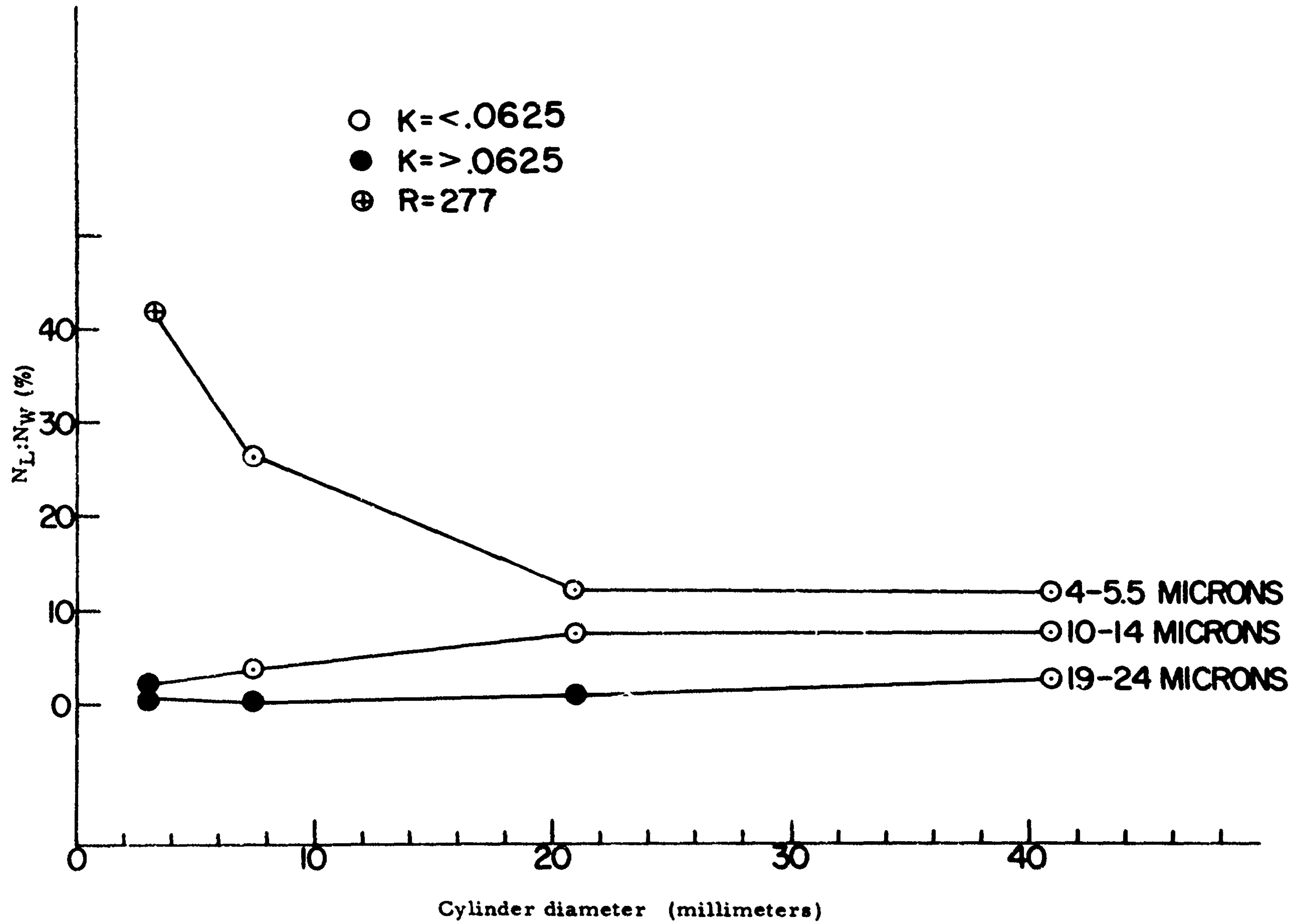

FIGURE 3

RATIO $N_L:N_W$ VERSUS CYLINDER DIAMETER AT VELOCITY = 3.1 MPH

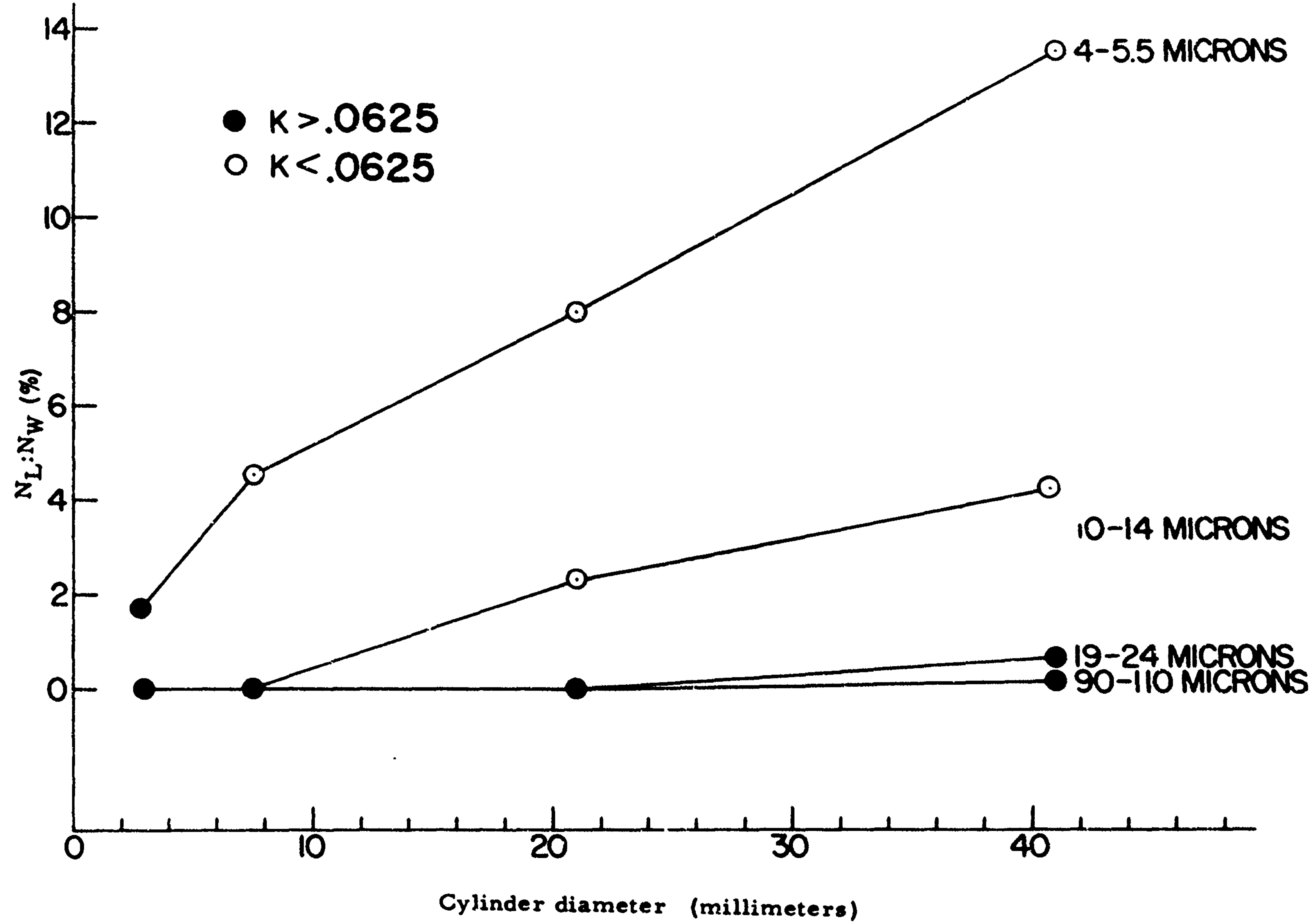

FIGURE 2

RATIO $N_L:N_W$ VERSUS CYLINDER DIAMETER AT WIND VELOCITY = 8.5 MPH

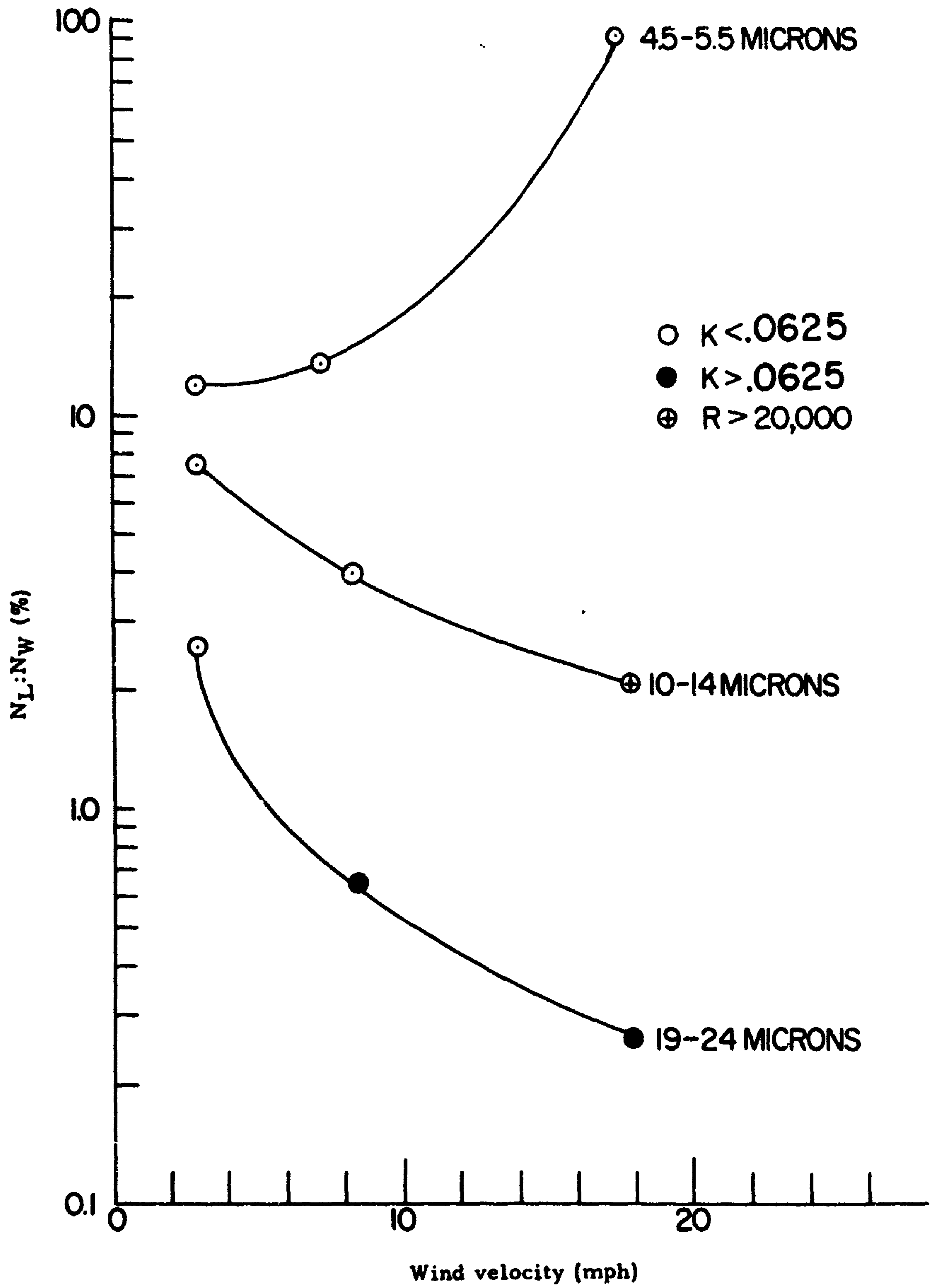

FIGURE 4

$N_L:N_W$ VERSUS WIND VELOCITY FOR 41-MM ROD

The fact that 30 min to 2 hr was required to obtain a countable deposition on the windward side when $K < 0.0625$ suggests a reason why some workers in the field of impaction were not able to find deposition. Exposure time was not long enough to obtain measurable amounts of deposit by the mechanism of turbulent diffusion.

C. Description of the Mechanism of Deposition by Turbulent Diffusion.

Deposition by turbulent diffusion on the side walls of a wind tunnel and a pipe have been discussed by Pereles[8] and Friedlander.[9]

Turbulence in the airflow causes particles to execute excursions at right angles to their mean trajectories. When the path of a particle approaches the surface of a cylinder, the lateral excursion of the particle may bring it into the boundary layer of the cylinder. Within the boundary layer, also turbulent, the particle executes further excursions and thus reaches the nonturbulent laminar sublayer lying immediately adjacent to the cylinder surface. If the stopping distance of the particle is greater than the thickness of the laminar sublayer (a few thousandths of an inch), the particle penetrates the sublayer and is deposited on the cylinder surface.

D. Discussion of Leeward Deposition.

1. Vortexes.

Leeward deposition is accounted for by the presence of vortexes in the wake of the cylinder. These vortexes have been measured and photographed. Description, photographs, and measurements are to be found in textbooks on fluid dynamics such as Goldstein,[10] Prandtl and Tietjens,[11] and Hoerner.[12]

A vortex is a rotational flow of fluid found in the wake of blunt objects such as spheres, cylinders, and plates. The size, strength, and nature of the vortex depends upon the Reynolds number of the flow based upon the diameter of the blunt object. At all Reynolds numbers, the direction of rotation is from the edge of the wake inward toward the center. There is, then, within the wake, a return flow of fluid toward the object, opposite in direction to that of the main flow.

At Reynolds numbers of approximately 10 and below, there are no vortexes in the wake. Between Reynolds numbers of 10 and 20, depending on the flow, two small vortexes, symmetrical and equal in size, appear behind the cylinder near the top and bottom. Between Reynolds numbers of 20 and 65, depending on the flow, the vortexes become larger but still cling to the surface of the cylinder and are of equal size and symmetrical. Between 65 and 300, the vortexes become unequal in size and asymmetrical. The larger vortex breaks off from the cylinder and travels downstream. In the meantime, the smaller one grows larger and breaks off. The breaking off is alternate and periodic and the eddies persist downstream. There is a strong return flow to the cylinder. The type of wake is called Von Karman street and is often seen in the wake of small boats.

Between Reynolds numbers of 300 and 1,600, the vortexes become elongated and move downwind, forming at some distance behind the cylinder. The return flow is weak.

At a Reynolds number of 1,600, the vortexes suddenly become shorter. Between 1,600 and 10,000, the distance between the formation of the vortexes and the cylinder shortens continuously. At Reynolds numbers of 10,000 to 20,000, the vortexes are formed at the surface and the return flow is strong. At a Reynolds number of 20,000, the wake becomes turbulent, and the vortex flow weakens because of the dissipating action of turbulence.

In the above discussion, cited values of R are approximate since the particular values at which the changes in the vortexes occur depend on the experimental conditions, such as the relative dimensions of the wind tunnel and cylinder and the intensity of upstream turbulence. The figures quoted here are for a wide tunnel with very low upstream turbulence.

2. Explanation of Leeward Deposition.

Pearcy and Hill[13] have given an account of leeward deposition of particles on a sphere in their paper on the coalescence of raindrops. They have shown that vortexes in the wake entrain particles of a smaller terminal velocity than their own velocity and, by rotational flow, bring the particles into the wake. The return flow carries the particles to the sphere, provided that its velocity is greater than their terminal velocity. In the application of these ideas to cylinders, it is to be expected that there would be, for a given particle size and wind velocity, greater leeward deposits when the return flow in the wake is strong, as it is in the Von Karman region and the region of

Reynolds numbers from 10,000 to 20,000. Table 2 shows that $N_L:N_W$ is indeed greater for a specified particle size and wind velocity in these two regions. Examples in the Von Karman region are the deposition of particles of the 19μ to 24μ range and smaller, moving at 3 mph toward a 3.1-mm rod. The corresponding Reynolds numbers were 277 and 293, at the upper limit of this region. Examples in the region of high Reynolds numbers are the deposition of particles of all sizes moving at 18 mph toward the 41-mm rods. The corresponding Reynolds numbers were 10,000 to 20,000, where $N_L:N_W$ was greater by one or two orders of magnitude than when the Reynolds number was smaller.

E. Anomalous Behavior.

The anomaly in $N_L:N_W$ that appeared in the deposition of 4.0μ to 5.5μ particles at 16.8 mph on rods of 21 and 41 mm may be explained as a turbulence effect. $N_L:N_W$ at R = 20,000 was 92% and at R = 10,000 was 131%, whereas for the larger particles it was greater for R = 20,000. The explanation is that wakes become turbulent at a lower Reynolds number because of greater upstream turbulence. Greater upstream turbulence was caused by full-length extension of the dispersal outlet tube in the wind tunnel. For the dispersion of the 4.0μ to 5.5μ particles the dispersal outlet tube extended from top to bottom of the wind tunnel, whereas for the dispersion of the larger particles the ejector extended only halfway down. Surveys of the wakes of the ejector in both extensions showed a greater velocity deficiency when it extended all the way to the floor. According to Eskinazi,[14] the larger velocity deficiency is associated with greater turbulence. The indication is that the greater upstream turbulence induces turbulence behind the cylinder at an R value lower than 20,000. The effect of the turbulence is to dissipate the strength of the vortexes.

F. Practical Considerations.

The results show that there was very little leeward deposition on cylinders of particles over 100μ from aerosols moving at velocities up to 18 mph. Thus, for practical purposes, no further consideration need be given to leeward deposition of particles over this size. There was, however, considerable leeward deposition of particles in the 5μ range. The heaviest leeward deposit occurred when the flow Reynolds number relative to the cylinder was between 10,000 and 20,000. Leeward deposit was then as great or greater than that on the windward side. Many cylindrical objects in field tests, for example, a man's arm held out in a wind of 4 mph, have a Reynolds number in this range. In calculations of the total amount of aerosol deposited on such a target, the leeward deposition should be taken into account.

Consideration of leeward deposition would increase the calculated amounts of aerosol reaching the target by as much as 100% or more in the case of particles of 5μ and less, and perhaps give more realistic estimates.

V. CONCLUSIONS.

It is concluded that, in general, there is little leeward (back) deposition of particles over 100μ in diameter, an intermediate number of particles between 10μ and 100μ depending on the conditions, and a large number of particles below 10μ in diameter at velocities from 3 to 18 mph.

When K was greater than the critical value of 0.0625, $N_L:N_W$ was 0.4% or less, and, in general, showed no variation with particle size, cylinder diameter, and wind velocity.

When K was less than 0.0625. $N_L:N_W$ ranged from about 0.5% to 131%, and, in general, increased with cylinder diameter and with decreasing particle size and wind velocity.

Exceptions to this general behavior were found at $R < 300$ and $> 10{,}000$. In these regions, $N_L:N_W$ was greater than expected. Since at these R's vortexes are near, or at, the cylinder surface on the leeward side, it is probable that vortexes in the wake play a role in leeward deposition.

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13 ABSTRACT

A study of leeward (back) deposition of moving aerosols on cylinders was conducted in a wind tunnel. Cylinder sizes were varied from 3.1 to 41 mm in diameter, aerosol particles from 4.5μ to 110μ in diameter, and wind velocities from 3 to 18 mph. There was little leeward deposition of particles over 100μ in diameter, an intermediate amount of deposition of particles between 10μ and 100μ in diameter (depending on conditions), and a large deposition of particles below 10μ in diameter at velocities from 3 to 18 mph. The ratio of leeward and windward particle count deposits on the cylinders were calculated from experimental results. The impaction parameter K and the Reynolds number of the airflow around the cylinder were also calculated. When K was greater than the critical value of 0.0625, the ratio was 0.4% or less, and showed no variation with particle size, cylinder diameter, and wind velocity. When K was less than 0.0625, the ratio ranged from about 0.5% to 131%. In general, the ratio increased with decreasing particle size and wind velocity and with increasing cylinder diameter.

14 KEYWORDS

Deposition	Velocity	Turbulence
Leeward	Parameter	Vortex
Windward	Impaction	Manometer
Aerosols	Particle count	Polystyrene powder
Cylinders	Reynolds number	Diameter
Particle size	Airflow	Calculation
Wind tunnel		

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